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ECLOGITES IN THE EASTERN ALPS: HIGH-PRESSURE METAMORPHISM IN THE CONTEXT OF THE ALPINE OROGENY

by

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The Alpine orogene formed during the convergence of the African and European plates, which has been more or less continuous since Cretaceous times. The geology of the Eastern Alps is complex, however, because of the existence of more than one oceanic realm and several microplates between Africa and Europe, and also because the interplay between shortening processes and lateral movements makes it difficult to determine the plate tectonic arrangement through time.

Models of Alpine tectonics have developed rapidly during recent decades, mainly as a result of modern structural, stratigraphic, petrological and geochronological investigations which, together with deep reflection seismic profiling and tomographic studies, have provided new insights into the present-day structures. Contrasting interpretations on the evolution of the Alpine orogen still remain, however, further complicated by the use of different nomenclatures. This summary of the geology of the Alps is based on the tectonic interpretation by SCHMID et al. (2004) and on the recent review of Alpine metamorphic history by OBERHÄNSLI (2004) together with all literature cited therein.

In a geographical sense the Alps are divided into the Southern Alps (to the south of the Periadriatic Lineament), the Eastern Alps, the Central Alps (approximately between NFP-20 WEST and NFP-20 EAST), and the arc of the Western Alps (Fig. 1). These divisions are each characterised by different paleogeographic elements that were incorporated at different stages in the Alpine tectonic evolution, resulting in distinct geological structures and a specific geomorphology.

1. Plate tectonics

The Alpine orogen is subdivided into plate tectonic units reflecting the Mesozoic to Paleogene paleogeography (Fig. 1, 2). In their simplest form the plate tectonic units involved in the Alpine orogen are the European continent, the Alpine Tethys ocean, the Apulian microcontinent and the Meliata ocean (FROITZHEIM et al., 1996).

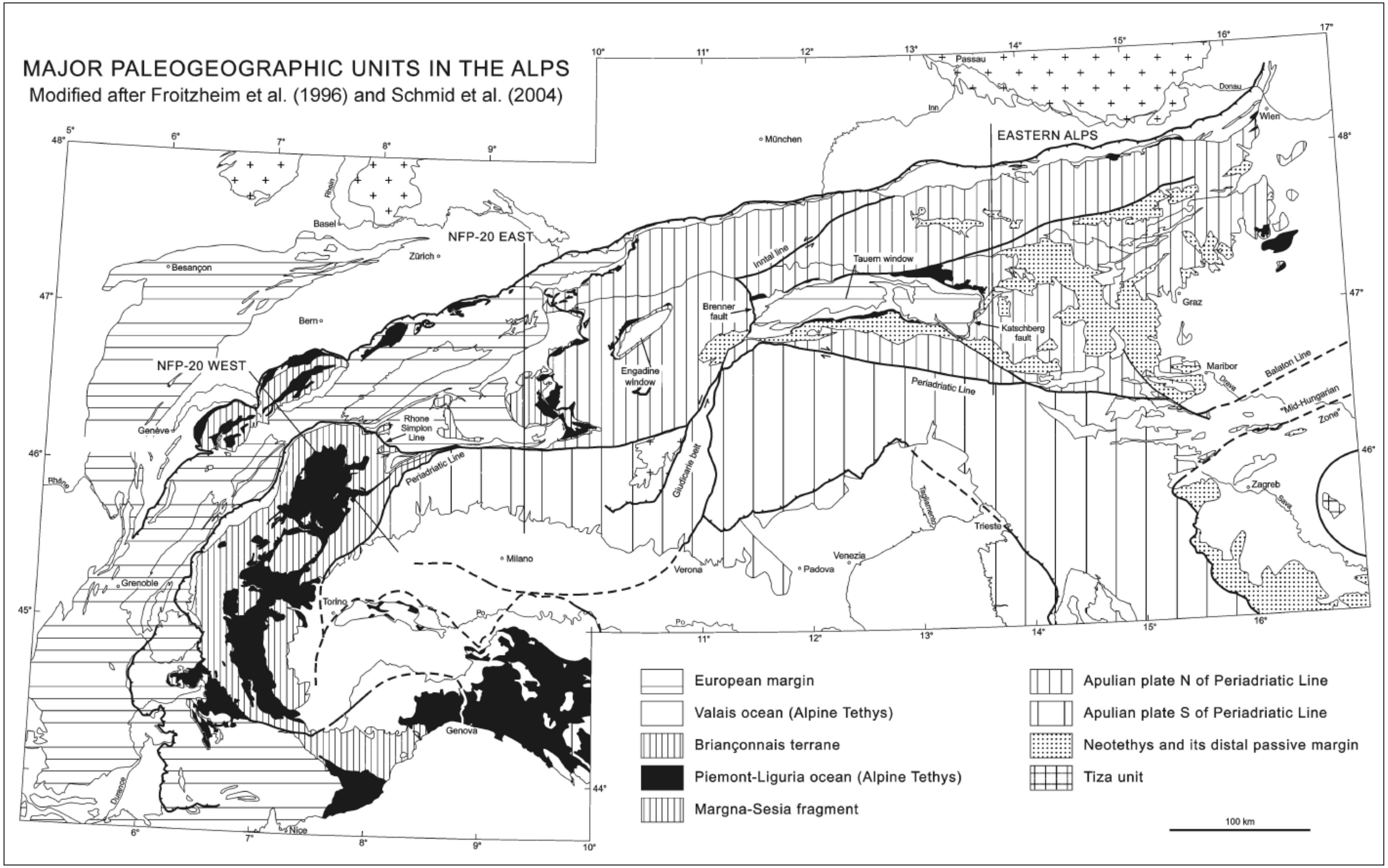

Fig. 1

Map of the major paleogeographic and tectonic units in the Alps adapted from SCHMID et al. (2004).

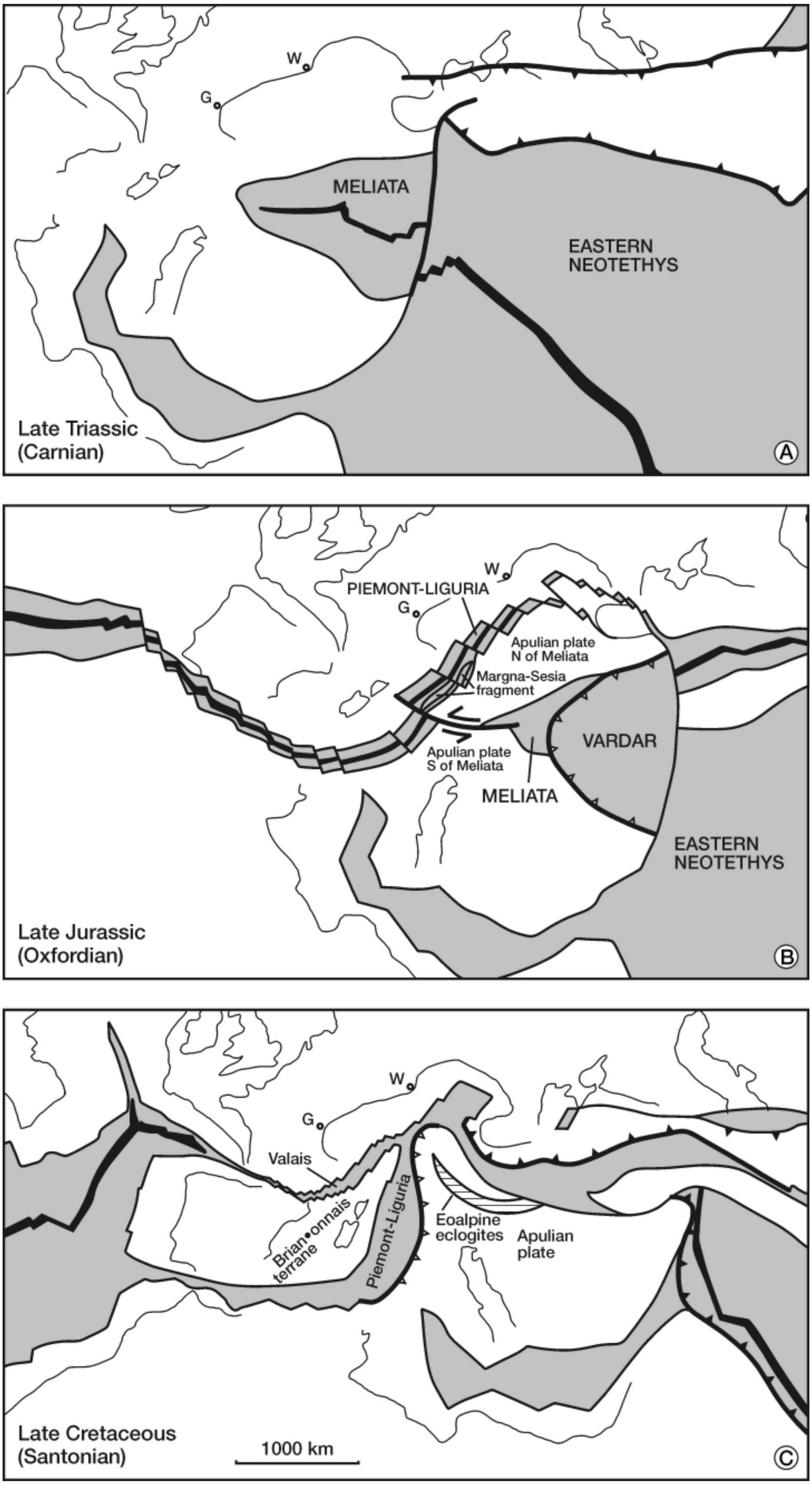

Fig. 2

Paleogeographic reconstruction for a) Late Triassic, b) Late Jurassic and c) Late Cretaceous times. G: Genève, W: Vienna adapted from SCHMID et al. (2004).

The Meliata ocean opened during the Triassic (KOZUR, 1992) when, according to STAMPFLI & BOREL (2004), it formed as a back arc ocean at the western end of the Tethys ocean bay, related to the closure of the Paleotethys ocean. During the Jurassic the Vardar ocean opened and the Meliata, Vardar and Neotethys oceans formed a continuous basin. The closure of the Meliata ocean started in the Jurassic and continued until Lower Cretaceous times, with the subsequent continental collisions being referred to as the eo-Alpine event. The geometry of these oceanic basins, their relationships and the plate tectonic arrangement during their closure is still under discussion (e.g. CHANELL & KOZUR, 1997; GAWLIK, et al., 1999; NEUBAUER et al., 2000; CSONTOS & VÖRÖS, 2004). Melange zones with material from the Triassic ocean are preserved in the Dinarides and in the Pannonian basin, whereas fragments with a Jurassic blueschist facies metamorphic imprint can be found in the Western Carpathians (DAL PIAZ et al., 1995). However, no oceanic Meliata suture is preserved in the Alps and outcrops of this realm are extremely scarce, only being found in the easternmost part of the Eastern Alps. Recent interpretations suggest that the eo-Alpine event in the Alps was related to intracontinental subduction within the Apulian microplate, which took place in the continuation of an oceanic subduction zone further to the southeast (THÖNI & JAGOUTZ, 1993; KURZ & FRITZ, 2003).

The Alpine Tethys ocean was related to the opening of the Atlantic ocean and consisted of two subbasins (FRISCH, 1979). At first the Piedmont-Ligurian ocean developed in the Jurassic and separated Apulia from Europe. During the Lower Cretaceous spreading in the Valais ocean cut off the Brianconnais microcontinent from southwestern Europe, while in the east the two oceans merged into a single basin (FROITZHEIM et al., 1996). The subduction of the Alpine Tethys started in the Upper Cretaceous and lasted until the Eocene. During the related continental collisions, which are referred to as the Alpine orogenic event, Europe acted as the lower tectonic plate and Apulia as the upper one. The suture zone of the Alpine Tethys is represented by the Penninic Nappes and can be traced all along the Alps.

2. Tectonic units

This description of the tectonic units of the Alps is based on the map and sections published by SCHMID et al. (2004) (Plate 1, Fig. 3; numbers in the text refer to these figures). From bottom to top (from N to S, or NW to SE, respectively) the Alps are made up of the following tectonic units:

2.1 Units derived from the (Mesozoic to Paleogene) European continent:
The European continent consists of a deeply eroded Variscan (Late Devonian to Carboniferous) metamorphic continental crust, rich in plutonic rocks (41 north of the Alpine front), covered by Carboniferous to Eocene sedimentary sequences (39, 40). This crust is still in contact with its lithospheric mantle; it dips beneath the Alps and contains the Late Eocene to Neogene Molasse basin (2, 38) which is the northern peripheral foreland basin of the orogene. The External massifs (41) represent windows in the European plate within the Western and Central Alps. They comprise basement rocks and Late Carboniferous to Cretaceous cover sequences. The Helvetic and Ultrahelvetic Nappes (36, 37) are a thin-skinned fold and thrust belt formed exclusively of detached cover sequences. The Helvetic Nappes at the northern margin of the Central Alps are well known, whereas in the Eastern Alps they are present only as thin slices.

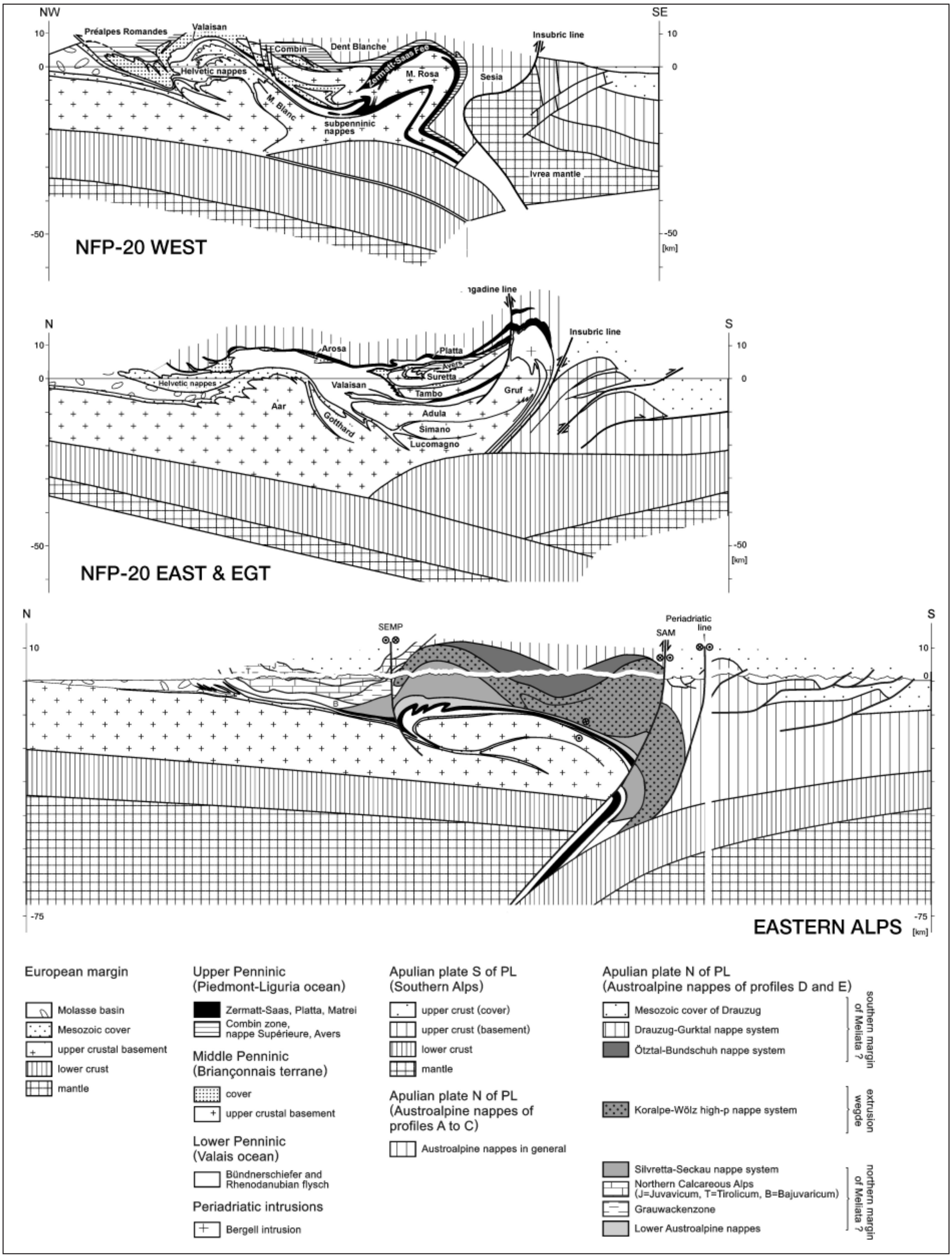

Fig. 3

Sections through the Western, Central and Eastern Alps adapted from SCHMID et al. (2004).

Plate 1

Tectonic map of the Alps adapted from SCHMID et al. (2004). Doted squares show the areas of Saualpe-Koralpe-Pohorje region and Tauern Window, which will be visited during the excursions.

The Sub-Penninic Nappes (33, 34) represent the distal European margin, forming ductilely deformed basement and cover nappes which lost contact with their lithospheric mantle and served as the basement for the Helvetic Nappes. They form the Gotthard, Travetsch and Adula Nappes in the Central Alps and also, contrary to many earlier publications, the Venediger Nappe system in the Tauern Window of the Eastern Alps. This interpretation is based on the conclusion that the crustal material of the Venediger Nappe system was not separated from the European margin by an oceanic basin (e.g. FROITZHEIM et al., 1996; KURZ et al., 2001). The eclogitic Sub-Penninic basement units (35) (Adula Nappe, Cima Lunga Nappe and Eclogite Zone of the Tauern Window) contain material derived from the Alpine Tethys ocean and developed in a tectonic accretion channel (KURZ et al. 1998a; ENGI et al., 2001; KURZ & FROITZHEIM, 2002).

2.2 Penninic Nappes:

The Penninic Nappes comprise three paleogeographic elements: the Piedmont-Ligurian ocean, the Brianconnais microcontinent and the Valais ocean.

The Piedmont-Ligurian ocean opened in Upper Jurassic times. Its initial sea-floor formed by exhumation of the subcontinental mantle of the Apulian microplate (FROITZHEIM & MANATSCHAL, 1996). These mantle rocks are overlain by Jurassic radiolarites, aptychus limestones and Cretaceous calcareous turbiditic metasediments. The Brianconnais microcontinent was a part of the European distal margin until it was cut off by the opening of the Valais ocean in the Cretaceous. The Valais oceanic crust comprises Cretaceous ophiolites overlain by Cretaceous to Eocene calcareous turbiditic metasediments. Towards the east the Valais ocean merged into the Piedmont-Ligurian basin thus forming a single oceanic basin in the east (e.g. STAMPFLI, 1994; FROITZHEIM et al., 1996). Although this situation in the east makes any subdivision of the Piedmont-Ligurian from the Valais basin there somewhat artificial (KURZ et al., 2001), characteristic successions, analyses of the source areas of the clastic sedimentary successions and the age and chemical characteristics of the ophiolitic rocks allow the differentiation of elements from the northern or southern part of this joint oceanic basin.

The Penninic Nappes can be subdivided into the Upper, Middle and Lower Penninic Nappes, whereby each consists mainly of one of the paleogeographic elements mentioned above.
The Lower Penninic Nappes (31, 32) consist predominantly of material from the Valais oceanic province and from the northern parts of the joint oceanic basin in the east. The Lower Penninic Nappes make up large parts of the Central Alps and the central part of the Lower Engadine Window. The lower nappes of the Rhenodanubian flysch zone (32) represent a continuation of the Central AlpineValais basin sediments into the Eastern Alps (KURZ et al., 1998b); they comprise Cretaceous flyschoid sediments deposited in a basin along the European margin. The Glockner Nappe system of the Tauern Window, consisting of calcareous flyschoid metasediments and metaophiolites, is thought to be a southern continuation of the lower nappes of the Rhenodanubian flysch zone.
The Middle Penninic Nappes (27, 28, 29, 30) are mainly derived from the Brianconnais microcontinent and are common in the Western and Central Alps. The easternmost nappes to include material from the Brianconnais microcontinent are represented by the Tasna Nappe of the Lower Engadine Window.

Rocks derived from the Piedmont-Ligurian ocean and the accretionary wedge along the southern margin of the oceanic basin towards the Apulian microcontinent made up the Upper Penninic Nappes (26). They are widespread in the Western and Central Alps and continue into the Apennines (9). In the Eastern Alps the Upper Penninic Nappes form the uppermost tectonic elements in the Engadine and Tauern windows (e.g. the Arosa Zone, the Matrei Zone, and the Reckner Complex) as well as the whole of the Rechnitz Window Group. In the northern part of the Eastern Alps the Ybbsitz klippen belt (DECKER, 1990) is a remnant of the Piedmont-Ligurian ocean, containing the typical sequence of serpentinites, Jurassic radiolarites and aptychus limestones. It is in contact with the Kahlenberg Nappe of the Rhenodanubian flysch zone, which is also interpreted to be an Upper Penninic Nappe (FAUPL & WAGREICH, 1992).

2.3 Apulian microcontinent:

The Apulian microcontinent consists of a Cadomian continental crust (NEUBAUER, 2002) with Paleozoic metasedimentary sequences and with magmatic activity related to rifting and subduction processes lasting until the Carboniferous. During the Variscan orogeny large parts of this crust were affected by metamorphic processes and synorogenic magmatism. Post-orogenic Permo-Carboniferous sediments were deposited locally. In the Permian the area was affected by lithospheric extension expressed by basaltic magmatic underplating, intense acidic magmatism and related high-temperature / low-pressure (HP/LT) metamorphism. More than 3 km of Permomesozoic sediments were subsequently deposited on top of the thermally subsiding microcontinent, which formed a broad carbonate shelf towards the Meliata ocean in the southeast and, from the Jurassic, was bordered to the north by a passive continental margin facing towards the Piedmont-Ligurian oceanic trough (Fig. 2). In the Alps the Apulian microcontinent is represented by the Margna-Sesia fragment and by the Austroalpine and Southalpine units, the latter two being separated by the Periadriatic lineament.

The Margna-Sesia fragment (25) (FROITZHEIM et al., 1996) rifted apart from the Apulian microcontinent during the Middle Jurassic. In the late Cretaceous it was incorporated in the accretionary wedge and subducted along the Apulian margin.

The Austroalpine unit forms a complex nappe stack of crustal material which can be subdivided into Lower and Upper Austroalpine units (Fig. 4). The Lower Austroalpine unit (24) formed the continental margin towards the Piedmont-Ligurian ocean and was affected by tectonism during the opening and closing of this oceanic realm (Alpine event). It overlies the Penninic Nappes of the Eastern Alps. The Upper Austroalpine unit represents an eo-Alpine nappe pile. Its lowermost unit is the Silvretta-Seckau Nappe system (23) consisting of a basement with a dominating Variscan metamorphic imprint and remnants of Permotriassic cover (parts of 19). During the eo-Alpine event it was overprinted by sub-greenschist to greenschist facies conditions.

To the north the Silvretta-Seckau Nappe system is overlain by the nappes of the Greywacke zone (18), which consists of greenschist facies metamorphic Paleozoic sequences, and the Juvavic (15), Tirolic (16) and Bajuvaric (17) nappe systems. The latter form the Northern Calcareous Alps, comprising unmetamorphosed to lowermost greenschist facies metamorphic Permomesozoic sediments deposited on the shelf facing originally towards the Meliata ocean, with the sequences of the Juvavic Nappe system representing the most distal shelf towards the oceanic basin.

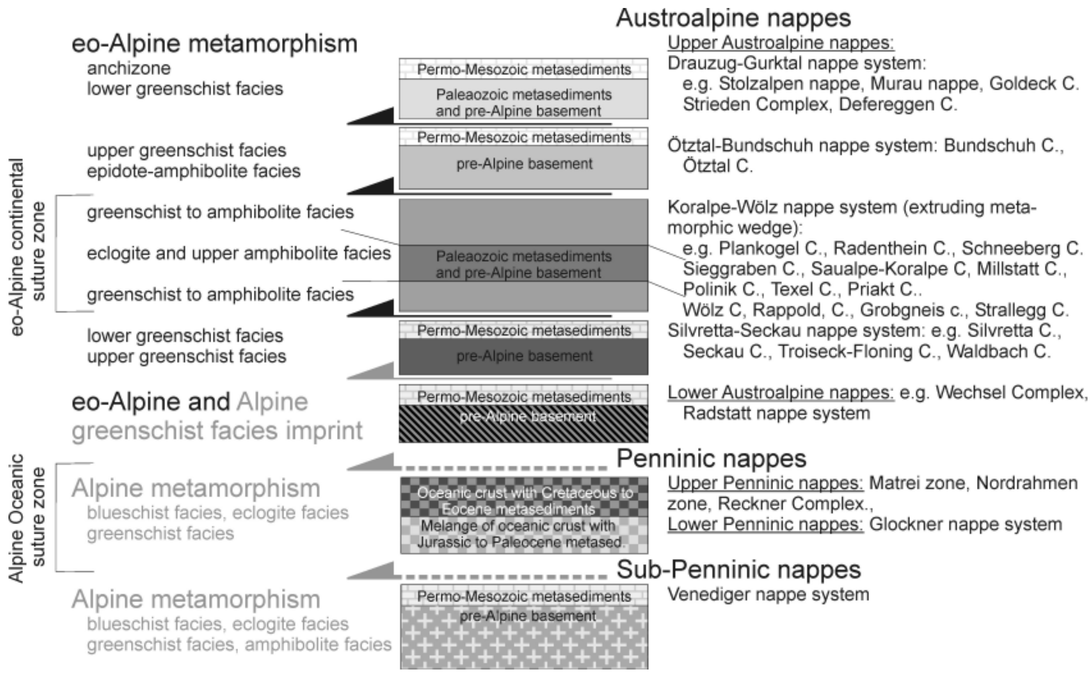

Fig. 4

Schematic nappe stack of the southeastern part of the Eastern Alps with information on the metamorphic grade and correlation with nappes from the western part of the Austroalpine units.

To the south the Silvretta-Seckau Nappe system is overlain by the Koralpe-Wölz Nappe system (22) which represents an eo-Alpine metamorphic extrusion wedge (SCHUSTER et al., 2004). Its Permomesozoic cover was completely stripped off during an early phase of the eo-Alpine orogenic event (Lower Cretaceous) and it therefore consists exclusively of polymetamorphic basement nappes with a Permotriassic HTLP (SCHUSTER et al., 2004) and an eo-Alpine LTHP metamorphic overprint (e.g. HOINKES et al., 1999).

The Ötztal-Bundschuh Nappe system (21 and parts of 19) shows a similar lithological composition to the Silvretta-Seckau Nappe system, but is positioned on top of the Koralpe-Wölz Nappe system. The overlying Drauzug-Gurktal Nappe system (20) is made up of a Variscan metamorphic basement, Paleozoic metasediments and Permomesozoic sequences (parts of 19). Within the Ötztal-Bundschuh and Drauzug-Gurktal Nappe systems the eo-Alpine metamorphic grade decreases upwards from amphibolite facies at the base to diagenetic conditions at the top of the nappe pile.

The Southalpine unit (11, 12, 13, 14) shows minor deformation concentrated along its margins. Its major part is in contact with a subcontinental lithosphere; this contact is visible at the surface in the Ivrea Zone in the Western Alps (11). The Southalpine unit is considered to be a southern external retro-arc orogenic wedge within the Alpine orogenic system (e.g. SCHMID et al., 1996). In the southeast the Southalpine unit continues into the External Dinarides (8).

2.4 Meliata zone:

The Meliata zone of the eastern Alps contains remnants of the Meliata oceanic basin. These include serpentinites, basic volcanic rocks and deep water Triassic sediments, redeposited in Jurassic metasediments. These rocks can be correlated with those from the Meliata zone in the Western Carpathians (MANDL, 2000).

The Meliata zone occurs as tiny klippen within the eastern part of the Eastern Alps between the Tirolic and Juvavic Nappe systems of the Austroalpine unit. They show a sub greenschist facies metamorphic imprint but no indications of subduction related HP/LT metamorphism. Material from the Meliata oceanic basin is also present as detritus in Cretaceous sediments of Austroalpine units (FAUPL & WAGREICH, 2000) and in the Haselgebirge, an evaporite tectonite at the base of the Juvavic Nappe system.

The Periadriatic intrusions (5) comprise calkalkaline tonalities, granodiorites and granites, and minor alkaline basaltic dikes. They are mostly Oligocene in age and related to the break-off of the Alpine Tethys oceanic lithosphere from the distal European margin (DAVIS & VON BLANKENBURG, 1995). Their intrusion is closely associated with contemporaneous strike-slip movements along the Periadriatic lineament.

3. Distribution and timing of high-pressure metamorphism within the Alps

The convergence of Africa and Europe led to the formation of the Alpine orogenic belt by "tectonic progradation" (FRISCH, 1979) from south to north. This process started with an intra-continental subduction within the Austroalpine unit in the Lower Cretaceous which was followed by the Upper Cretaceous-Eocene subduction of the Piedmont-Ligurian and Valais ocean and prograding continental collisional events that continued until recent times. This mechanism produced high-pressure metamorphism in different tectonic units, decreasing in age from south (internal) to north (external).

A brief summary of this evolution is given below. Detailed reviews of the metamorphic conditions and the timing of metamorphism in the individual units, together with maps showing the distribution of the metamorphic grade, are given by FREY et al. (1999) and OBERHÄNSLI (2004).

3.1. Eclogite formation in the eo-Alpine subduction zone:
In the Alps the eo-Alpine eclogites only occur in the Koralpe-Wölz Nappe system of the Austroalpine unit. None of these eclogites are metamorphosed remnants of oceanic crust from the Maliata ocean. Most of them derived from pre-existing amphibolites and only a minor part (in the Saualpe-Koralpe Complex) formed from Permian gabbros and basalts intruded into metasedimentary rocks (MILLER & THÖNI, 1997). Furthermore, the absence of blueschist facies metamorphic precursor assemblages or associated rocks argues against eclogite formation as a consequence of oceanic subduction (GAWLIK et al., 1999; NEUBAUER et al., 2000) and in favour of a continental subduction setting, possibly in the lateral continuation of an oceanic subduction zone (THÖNI & JAGOUTZ, 1993, KURZ & FRITZ, 2003; JANAK et al., 2004).

The following description of the eo-Alpine event is based on the interpretation proposed by SCHUSTER (2004). At the end of the Jurassic the Austroalpine unit showed the following zoning. Firstly, in the northwest, the Lower Austroalpine unit formed a passive margin towards the Alpine Tethys. Next came the future Silvretta-Seckau Nappe system, overlain by the lower nappes of the future Greywacke zone and by the Bajuvaric Nappe system.

Further to the southeast was the future Koralpe-Wölz Nappe system, with the uppermost nappe of the Greywacke zone (Noric Nappe) overlain by the future Tirolic Nappe system and the already existing Juvavic Nappe system above. To the south of a system of Jurassic sinistral strike-slip faults, the future Ötztal-Bundschuh and Drauzug-Gurktal Nappe systems and the Southalpine unit where located. The latter tree units shifted to the south of the Juvavic Nappe system during the activity of the Jurassic sinistral strike-slip faults. During the lowermost Cretaceous the system of strike slip faults was transformed into a southeast-dipping continental subduction zone. When the subduction started (in the Beriassian, ~140 Ma) the cover of the tectonic lower plate in the northwest (the uppermost nappe of the Greywacky zone, Tirolic and Juvavic Nappe systems) was stripped off from its basement (the future Koralpe-Wölz Nappe system) and thrust towards the northwest. The basement was subducted below the tectonic upper plate to the southeast, with maximum depths being reached in the middle Cretaceous (THÖNI 1999, 2002). The Koralpe-Wölz Nappe system subsequently formed by exhumation in a extrusion wedge, by thrusting in the lower part of the wedge and normal faulting in the upper part.. The main part of the nappe was exhumed in a pro-wedge geometry (e.g. Saualpe-Koralpe and Sieggraben Complexes), whereas to the southwest (Texel Complex) and southeast (Millstatt Complex) of the recent Tauern Window a retro-wedge geometry developed. During normal faulting late-orogenic to post-orogenic basins (sediment basins of the Gosau Group) formed on top of the upper plate and on top of the Bajuvaric, Tirolic and Juvavic nappe system, which form the Northern Calcareous Alps.

From the late Eocene onwards the Austroalpine unit was affected by deformation caused by the exhumation of Penninic and Sub-Penninic Nappes within windows (GENSER & NEUBAUER, 1989; FÜGENSCHUH et al., 1997) and by lateral extrusion towards the east (RATSCHBACHER et al. 1989). During these processes a system of normal and strike slip faults developed, with remarkable vertical displacements in some places, cutting through the eo-Alpine nappe pile and exerting a strong control on the present day geographical distribution of eclogite occurrences.

In the Koralpe-Wölz Nappe system eclogite-bearing complexes can be traced from the Texel Complex southwest of the Tauern Window to the eclogite type locality in the Saualpe-Koralpe Complex, east of the Tauern Window (HAUY, 1822), and to the Sieggraben Complex at the eastern margin of the Alps. For the westernmost Texel Complex minimum pressures are 10-12 kbar at 550°C (HOINKES et al., 1991; SÖLVA et al., 2001). For the Prijakt Complex and the Polinik Complex to the south of the Tauern Window minimum pressures of approximately 15 kbar were reported by LINNER (1995) and HOKE (1990) respectively. Data on the eclogites from the Millstatt Complex to the southeast of the Tauern Window are >12 kbar at 600-630 °C (TEIML & HOINKES, 1996). In the northern part of the Saualpe-Koralpe Complex peak pressures of 15-20 kbar and 600-700°C have been recorded (MILLER, 1990; THÖNI & MILLER, 1996; MILLER & THÖNI, 1997), whereas for the southern part UHP metamorphic conditions with pressures > 30 kbar at 750-800°C were reported (Pohorje mountains, Slovenia; JANAK et al., 2004). Finally, for the eclogites of the Sieggraben Complex temperatures of 670-750°C at about 15 kbar were determined (NEUBAUER et al., 1999; PUTIS et al., 2002).

These data show regional trends: 1) The highest PT conditions were reached in the Saualpe-Koralpe Complex to the east of the Tauern Window, whereas to the west and to the east lower conditions have been determined. 2) Within the Saualpe-Koralpe Complex a southward increase

in maximum P and T can be recognised. This is consistent with a southward subduction direction in the Cretaceous (FLÜGEL & FAUPL, 1987; FRANK, 1987).
The timing of the eclogite facies metamorphism is best constrained by Sm-Nd garnet ages from the Saualpe-Koralpe and Texel Complexes indicating an age between 110 and 90 Ma. However many reliable data scatter around 95 Ma (Cenomanian) (for a review see THÖNI, 1999, 2002).

3.2. High-pressure metamorphism in the Alpine subduction zone:
The high-pressure rocks in the Alpine subduction zone formed as a result of the successive subduction of the Piedmont-Ligurian ocean, including the Margna-Sesia fragment, the Brianconnais microcontinent, the Valais ocean and, finally, the European margin, below the Apulian microcontinent.

Subduction of the Piedmont-Ligurian oceanic crust beneath the northern margin of Apulia started in the Upper Cretaceous. The continental Margna-Sesia fragment located within the ocean must have entered the subduction zone quite early, because eclogite facies metamorphism is documented within the Sesia Zone of the Western Alps at the Cretaceous-Tertiary boundary (60-70 Ma) (RUBATTO et al., 1999; DAL PIAZ et al., 2001; HANDY & OBERHÄNSLI, 2004).

In the Upper Penninic Nappes of the Western and Central Alps an eclogite facies imprint and locally UHP conditions were attained (approx. 28 kbar at 600-650°C; REINECKE, 1998; VAN DER KLAUW et al., 1997; AMATO et al., 1999), but only blueschist facies conditions were attained in the eastern part of the Central Alps and in the Eastern Alps (OBERHÄNSLI, 2004). In the Eastern Alps the Idalpe ophiolite in the Engadine Window experienced blueschist facies conditions of 7-9 kbar and c. 350°C (HÖCK & KOLLER, 1987). Within the Tauern Window the Matrei zone and the Reckner Ophiolite Complex experienced a blueschist facies metamorphic imprint, with conditions of 10 kbar pressure and c. 350°C, dated at approx. 50-45 Ma (DINGELDEY et al., 1997; HEIDORN et al., 2002). The blueschist facies imprint in the Rechnitz Window Group reached minimum pressures of 6-8 kbar at 330-370°C (KOLLER, 1985). An age of about 57 Ma has been suggested for the HP-imprint by Ratschbacher et al. (2005), based on an Ar-Ar measurement on amphibole. Although the subduction of the Piedmont-Ligurian ocean may have started in the Cretaceous the preserved high-pressure rocks are Paleocene to Lower Eocene (45-60 Ma) in age (e.g. DINGELDEY et al., 1997, CLIFF et al., 1998; RUBATTO et al., 1999; GEBAUER, 1999).

The subduction of the Brianconnais below the Upper Penninc Nappes started in the Eocene (SCHMID et al., 1996). Radiometric age data on the high-pressure rocks from the Middle Penninic Nappes are in the range of 30-40 Ma (e.g. GEBAUER et al. 1997; DUCHENÈ et al. 1997; RUBATTO & HERMANN, 2001). In the Western Alps the Middle Penninic Nappes show a metamorphic zoning with eclogite facies and local UHP conditions (c. 28-35 kbar and 700-750°C Dora Maira massif; CHOPIN et al., 1991) in the more internal units, and blueschist followed eventually by greenschist facies conditions towards the external units. In the Central Alps only blueschist facies conditions have been observed to date.

Since the youngest sediments derived from the Valais oceanic basin, which experienced high-pressure metamorphism, are Lutetian (40-48 Ma) in age, the peak of the metamorphic imprint in the Lower Penninic Nappes has to be younger than 45 Ma (FROITZHEIM et al., 1996). In the Lower Penninic Nappes eclogitic facies metamorphism is only documented in some localities of the Western and Central Alps (Versoyen and Antrona; BOUSQUET et al., 2002) and in the Tauern Window of the Eastern alps (Glockner Nappe; PROYER et al., 1999; DACHS & PROYER, 2001). Large parts of the Western and Central Alps experienced blueschist facies conditions, whilst in the Eastern Alps blueschist facies metamorphism is documented locally from the Engadine and Tauern Windows.

In the Sub-Penninic Nappes eclogites occur in the southern, tectonically uppermost, nappes, whereas large areas experienced a blueschist facies imprint. The age of the high-pressure imprint is Eocene (35-45 Ma) (DROOP et al., 1990; BECKER, 1993; GEBAUER, 1999; ZIMMERMANN et al., 1994; RATSCHBACHER et al., 2005) and a subsequent greenschist to upper amphibolite facies thermal overprint is characteristic. In the Central Alps, the Adula Nappe and the attached Cima Lunga unit experienced maximum conditions of 35 kbar at 850-900°C (NIMIS & TROMMSDORFF, 2001). For eclogites from the Eclogite Zone, located in the Tauern Window of the Eastern Alps, peak conditions of 20-22 kbar and 600-625°C have been reported (HOLLAND, 1979; HOSCHEK, 2001).

References

AMATO, J. M., JOHNSON, C. M., BAUMGARTNER, L. P. & BEARD, B. L. (1999): Rapid exhumation of the Zermatt-Saas ophiolite deduced from high-precision Sm-Nd and Rb-Sr geochronology. - Earth Planet. Sci. Lett., 171: 425-438.

BECKER, H. (1993): Garnet peridodite and eclogite Sm-Nd mineral ages from the Lepontine dome (Swiss Alps): New evidence for Eocene high-pressure metamorphism in the central Alps. - Geology, 21: 599-602.

BOUSQUET, R., GOFFÉ, B., VIDAL, O., OBERHÄNSLI, R. & PATRIAT, M. (2002): The tectono-metamorphic history of the Valaisan domain from the Western to the Central Alps: New constraints on the evolution of the Alps. - Geol. Soc. Amer. Bull., 114: 207-225.

CHANNEL, J. E. T. & KOZUR, H. W. (1997): How many oceans? Meliata, Vardar, and Pindos oceans in Mesozoic Alpine paleogeography. - Geology, 25: 183-186.

CHOPIN, C., HENRY, C. & MICHARD, A. (1991): Geology and petrology of the coesite-bearing terrain, Dora Maira massif, Western Alps. - Eur. J. Miner., 3: 263-291.

CLIFF, R. A., BARNICOAT, A. C. & INGER, S. (1998): Early Tertiary eclogite facies metamorphism in the Monviso Ophiolite. - J. metamorphic Geol., 16: 447-455.

CSONTOS, L. & VÖRÖS, A. (2004): Mesozoic plate tectonic reconstruction of the Carpathian region. - Palaeogeography, Palaeoclimatology, Palaeoecology, 210: 1-56.

DACHS, E. & PROYER, A. (2001): Relics of high-pressure metamorphism from the Grossglockner region, Hohe Tauern, Austria: Pragenetic evolution and PT-paths of retrogressed eclogites. - Eur. J. Mineral., 13: 67-86.

DAL PIAZ, G. V., CORTIANA, G., DEL MORA, A., MARTIN, S., PENNACHIONI, G. & TARTAROTTI, P. (2001): Tertiary age and paleostructural inferences of the eclogitic imprint in the Austroalpine outliers and Zermatt-Saas ophiolite, western Alps. - Int. J. Earth Sciences (Geol. Rdsch.), 90: 668-684.

DAL PIAZ, G. V., MARTIN, S., VILLA, I. M., GOSSO, G. & MARSCHALKO, R. (1995): Late Jurassic blueschist facies pebbles from the Western Carpathian orogenic wedge and paleostructural implications for western Tethys evolution. - Tectonics, 14: 874-885.

DAVIS, H. J. & VON BLANKENBURG, F. (1995): Slab breakoff: A model of lithospheric detachment and ist test in the magmatism and deformation of collisional orogenes. - Earth Planet. Sci. Let., 129: 85-102.

DECKER, K. (1990): Plate tectonics and pelagic facies: Late Jurassic to Early Cretaceous deep-sea sediments of the Ybbsitz ophiolite unit (Eastern Alps, Austria). - Sedimentary Geology, 67: 85-99.

DINGELDEY, CH., DALLMEYER, R. D., KOLLER, F. & MASSONE, H.-J. (1997): P-T-t history of the Lower Austroalpine nappe complex in the "Tarntaler Berge" NW of the Tauern Window: implications for the geotectonic evolution of the central Eastern Alps. - Contrib. Mineral. Petrol., 129: 1-19.

DROOP, G. T. R., LOMBARDO, B. & POGNATE, U. (1990): Formation and distribution of eclogite facies rocks in the Alps. - In: CARSWELL, D. A. (Ed.): Eclogite Facies Rocks. - (Blackie) Glasgow, 225-259.

DUCHENÉ, S., BLICHERT-TOFT, J., LUAIS, B., TELOUK, P., LARDEAUX, J.-M. & ALABAREDE, F. (1997): The Lu-Hf dating of garnets and the ages of Alpine high-pressure metamorphism. - Nature, 387: 586-589.

ENGI, M., BERGER, A. & ROSELLE, G. T. (2001): Role of the tectonic accretion channel in collisional orogeny. - Geology, 29: 1143-1146.

FAUPL, P. & WAGREICH, M. (1992): Cretaceous flysch and pelagic sequences of the Eastern Alps: correlations, heavy minerals, and paleogeographic implications. - Cretaceous Res., 13: 387-403.

FAUPL, P. & WAGREICH, M. (2000): Late Jurassic to Eocene palaeogeography and geodynamic evolution of the Eastern Alps. - Mitt. österr. geol. Ges., 92 (1999): 79-94.

FLÜGEL, H. W. & FAUPL, P. (Eds.) (1987): Geodynamics of the Eastern Alps. - (Deuticke) Wien, 418 pp.

FRANK, W. (1987): Evolution of the Austroalpine elements in the Cretaceous. - In: FLÜGEL, H. W. & FAUPL, P. (Eds.): Geodynamics of the Eastern Alps. - (Deuticke) Wien, 379-406.

FREY, M., DESMONS, J. & NEUBAUER, F. (1999): The new metamorphic map of the Alps: Introduction. - Schweiz. mineral. petrogr. Mitt., 79: 1-4.

FRISCH, W. (1979): Tectonic progradation and plate tectonic evolution of the Alps. - Tectonophysics, 60: 121-139.

FROITZHEIM, N. & MANATSCHAL, G. (1996): Kinematics of Jurassic rifting, mantle exhumation, and passive margin formation in the Austroalpine and Penninic nappes (eastern Switzerland). - Geol. Soc. Amer. Bull., 108: 1120-1133.

FROITZHEIM, N., SCHMID, S. M. & FREY, M. (1996): Mesozoic paleogeography and the timing of eclogite facies metamorphism in the Alps: A working hypothesis. - Eclogae geol. Helv., 89: 81-110.

FÜGENSCHUH, B., SEWARD, D. & MANCKTELOW, N. (1997): Exhumation in a convergent orogen: the western Tauern window. - Terra Nova, 9: 213-217.

GAWLIK, H.-J., FRISCH, W., VECSEI, A., STEIGER, T. & BÖHM, F. (1999): The change from rifting to thrusting in the northern Calcareous Alps as recorded in Jurassic sediments. - Geol. Rdsch., 87: 644-657.

GEBAUER, D. (1999): Alpine geochronology of the Central and Western Alps: new constraints for a complex geodynamic evolution. - Schweiz. mineral. petrogr. Mitt., 79: 191-208.

GEBAUER, D., SCHERTL, H.-P., BRIX, M. & SCHREYER, W. (1997): 35 Ma old ultrahigh-pressure metamorphism and evidemce for rapid exhumation in the Dora Maira Massif, Western Alps. - Lithos, 41: 5-24.

GENSER, J. & NEUBAUER, F. (1989): Low angle normal faults at the eastern margin of the Tauern window (Eastern Alps). - Mitt. österr. geol. Ges., 81: 233-243.

HANDY, R. M. & OBERHÄNSLI, R. (2004): Explanatory notes to the map: Metamorphic structure of the Alps. Age map of the metamorphic structure of the Alps - Tectonic interpretation and outstanding problems. - Mitt. österr. geol. Ges., 149: 201-226.

HAUY, R.-J. (1822): Traité de minéralogie, Secondé édition, revue, corrigée et considérablement augmentée par l´auteur. - Bachelier et Huizard, Paris.

HEIDRON, R., NEUBAUER, F., GENSER, J. & HANDLER, R. (2002): $^{40}Ar/^{39}Ar$ mica age constraints for the tectonic evolution of the Lower Austroalpine to Penninic boundary, Austria. - Mem. Sci. Geol., 54: 217-220.

HÖCK, V. & KOLLER, F. (1987): The Idalp ophiolite (Lower Engadine Window, Eastern Alps) its petrology and geochemistry. - Ofioliti, 12/1: 179-192.

HOINKES, G., KOLLER, F., RANTITSCH, G., DACHS, E., HÖCK, V., NEUBAUER, F. & SCHUSTER, R. (1999): Alpine metamorphism of the Eastern Alps. - Schweiz. mineral. petrogr. Mitt., 79: 155-181.

HOINKES, G., KOSTNER, A. & THÖNI, M. (1991): Petrologic constraints for Eoalpine eclogite facies metamorphism in the Austroalpine Ötztal Basement. - Mineralogy and Petrology, 43: 237-254.

HOKE, L. (1990): The Altkristallin of the Kreuzeck Mountains, SE Tauern Window, Eastern Alps - Basement Crust in a Convergent Plate Boundary Zone. - Jb. Geol. B.-A., 133: 5-87.

HOLLAND, T.J.B. (1979): High water activities in the generation of high pressure kyanite eclogites in the Tauern Window, Austria. - J. Geol., 87: 1-27.

HOSCHEK, G., 2001. Thermobarometry of metasediments and metabasites from the Eclogite zone of the Hohe Tauern, Eastern Alps, Austria. - Lithos, 59: 127-150.

JANAK, M., FROITZHEIM, N., LUPTÁK, B., VRABEC, M. & KROGH RAVNA, E.J. (2004): First evidence for ultrahigh-pressure metamorphism in Pohorje, Slovenia: Tracing deep continental subduction in the Eastern Alps. - Tectonics, 23: 2004TC001641.

KOLLER, F. (1985): Petrologie und Geochemie der Ophiolithe des Penninikums am Alpenostrand.- Jb. Geol. B.-A., 128/1: 85-150.

KOZUR, H. (1992): The evolution of the Meliata-Hallstatt ocean and its significance for the early evolution of the Eastern Alps and Western Carpathians. - Paleogeogr. Paleoclimat. Paleoecol., 87: 109-135.

KURZ, W. & FRITZ, H. (2003): Tectonometamorphic evolution of the Austroalpine nappe complex in the central Eastern Alps - consequences for the Eo-Alpine evolution of the Eastern Alps. - Internat. Geology Review, 45: 100-1127.

KURZ, W. & FROITZHEIM, N. (2002): The exhumation of eclogite-facies metamorphic rocks - a review of models confronted with examples from the Alps. - Internat. Geology Review, 44: 702-743.

KURZ, W., NEUBAUER, F. & DACHS, E. (1998): Eclogite meso- and microfabrics: implications for the burial and exhumation history of eclogites in the Tauern Window (Eastern Alps) from P-T-d paths. - Tectonophysics, 285: 183-209.

KURZ, W., NEUBAUER, F., GENSER, J. & DACHS, E. (1998): Alpine geodynamic evolution of passive and active continental margin sequences in the Tauern Window (Eastern Alps, Austria, Italy): a review. - Geol. Rdsch., 87: 225-242.

KURZ, W., NEUBAUER, F., GENSER, J., UNZOG, W. & DACHS, E. (2001): Tectonic evolution of Penninic Units in the Tauern Window during the Paleogene: Constraints from structural and metamorphic geology. In: PILLER, W. E. & RASSER, M. W. (Eds.), Paleogene of the Eastern Alps. - Österr. Akad. Wiss., Schriftenr. Erdwiss. Komm. 14, 347-375.

LINNER, M. (1995): Das ostalpine Kristallin der südwestlichen Schober-Gruppe mit den frühalpidischen Eklogiten im Bereich der Prijakte-Alkuser See-Schleinitz. - Geol. B.-A., Arbeitstagung 1995: 15-21.

MANDL, G. W. (2000): The Alpine sector of the Tethyan shelf - Examples of Triassic to Jurassic sedimentation and deformation from the Northern Calcareous Alps. - Mitt. österr. geol. Ges., 92: 61-78.

MILLER, Ch. (1990): Petrology of the type locality eclogites from the Koralpe and Saualpe (Eastern Alps), Austria. - Schweiz. mineral. petrogr. Mitt., 70: 287-300.

MILLER, CH. & THÖNI, M. (1997): Eo-Alpine eclogitization of Permian MORB-type gabbros in the Koralpe (Eastern Alps, Austria): new geochronological, geochemical and petrological data. - Chem. Geol., 137: 283-310.

NEUBAUER, F. (2002): Evolution of late Neoproterozoic to early Palaeozoic tectonic elements in Central and Southeast European Alpine mountain belts: review and synthesis. - Tectonophysics, 352: 87-103.

NEUBAUER, F., DALLMEYER, R.D. & TAKASU, A. (1999): Conditions of eclogite formation and age of retrogression within the Sieggraben unit, Eastern Alps: Implications for Alpine-Carpathian tectonics. - Schweiz. mineral. petrogr. Mitt., 279: 297-307.

NEUBAUER, F., GENSER, J. & HANDLER, R. (2000): The Eastern Alps: Result of a two-stage collision process. - Mitt. österr. geol. Ges., 92 (1999): 117-134.

NIMIS, P. & TROMMSDORFF, V. (2001): Revised thermobarometry of Alpe Arami and other garnet peridotites from the Central Alps. - J. Petrol., 42: 103-115.

OBERHÄNSLI, R. (Ed.) (2004): Metamorphic structure of the Alps. - Mitt. Österr. Miner. Ges., 149: 115-226.

PROYER, A., DACHS, E. & KURZ, W. (1999): Relics of high-pressure metamorphism from the Großglockner region, Hohe Tauern, Austria: Textures and mineral chemistry of retrogressed eclogites. - Mitt. österr. geol. Ges., 90: 43-56 .

PUTIS, M., KORIKOVSKY, S., WALLBRECHER, E., UNZOG, W., OLESEN, N. O. & FRITZ, H. (2002): Evolution of an eclogitized continental fragment in the Eastern Alps (Sieggraben, Austria). - J. struct. Geol., 24: 339-357.

RATSCHBACHER, L., DINGELDEY, Ch., MILLER, Ch., HACKER, B. R. & MCWILLAMS, M. O. (2005): Formation, subduction, and exhumation of Penninic oceanic crust in the Eastern Alps: time constraints from $^{40}Ar/^{39}Ar$ geochronology. - Tectonophysics, 394: 155-170.

RATSCHBACHER, L., FRISCH, W., NEUBAUER, F., SCHMID, S. M. & NEUGEBAUER, J. (1989): Extension in compressional orogenic belts: The Eastern Alps. - Geology, 17: 404-407.

REINECKE, T. (1991): Very-high-pressure metamorphism and uplift of coesite-bearing metasediments from the Zermatt-Saas zone, Western Alps. - Eur. J. Mineral., 3: 7-17.

RUBATTO, D., GEBAUER, D. & COMPAGNONI, R. (1999): Dating of eclogite-facies zircons: the age of Alpine metamorphism in the Sesia-Lanzo Zone (Western Alps). - Earth Planet. Sci. Lett., 167: 141-158.

RUBATTO, D. & HERMANN, J. (2001): Exhumation as fast as subduction? - Geology, 29: 3-6.

SCHMID, S. M., FÜGENSCHUH, B., KISSLING, E. & SCHUSTER, R. (2004): Tectonic map and overall architecture of the Alpine orogen. - Eclogae geol. Helv., 97: 93-117.

SCHMID, S. M., PFIFFNER, O.A., FROITZHEIM, N., SCHÖNBORN, G. & KISSLING, E. (1996): Geophysical-geological transect and tectonic evolution of the Swiss-Italian Alps. - Tectonics, 15: 1036-1064.

SCHUSTER, R. (2004). The Austroalpine crystalline units in the Eastern Alps. - Abstract Vol. PANGEO 2004, Ber. Inst.Erdwiss. K.-F.-Univ. Graz, 9: 30-36.

SCHUSTER, R., KOLLER, F., HOECK, V., HOINKES, G. & BOUSQUET, R. (2004): Explanatory notes to the map: Metamorphic structure of the Alps - Metamorphic evolution of the Eastern Alps. - Mitt. Österr. Miner. Ges., 149: 175-199.

SÖLVA, H., THÖNI, M., GRASEMANN, B. & LINNER, M. (2001): Emplacement of eo-Alpine high-pressure rocks in the Austroalpine Ötztal complex (Texel group, Italy/Austria). - Geodinamica Acta, 14: 345-360.

STAMPFLI, G. M. (1994): Exotic terrains in the Alps: a solution for a single Jurassic ocean. - Schweiz. mineral. petrogr. Mitt., 74: 449-452.

STAMPFLI, G. M. & BOREL, G. D. (2004): The TRANSMED transsects in space and time: constraints on the paleotectonic evolution of the Mediterranian domain. - In: CAVAZZA, W., ROURE, F., SPAKMAN, W., STAMPFLI, G. M. & ZIEGLER, P. A. (eds): The TRANSMED Atlas: the Mediterranean region from crust to mantle. - (Springer) Wien - New York, 53-70.

TEIML, X. & HOINKES, G. (1996): Der P-T-Pfad der Millstätter Serie und ein Vergleich mit dem südliche Ötz-tal-Stubai-Kristallin. - Mitt. Österr. Miner. Ges., 141: 228-229.

THÖNI, M. (1999): A review of geochronological data from the Eastern Alps. - Schweiz. Mineral. Petrogr. Mitt., 79/1: 209-230.

THÖNI, M. (2002): Garnet chronometry in the Eastern Alps: insight into the polyphase nature of a composite orogenic structure. - Mem. Sci. Geol., 54: 163-166.

THÖNI, M. & JAGOUTZ, E. (1993). Isotopic constraints for eo-Alpine high-P metamorphism in the Austroalpine nappes of the Eastern alps: bearing on Alpine orogenesis. - Schweiz. mineral. petrogr. Mitt., 73: 177-189.

THÖNI, M. & MILLER, Ch. (1996): Garnet Sm-Nd data from the Saualpe and Koralpe (Eastern Alps, Austria): chronological and P-T constraints on the thermal and tectonic history. - J. metamorphic Geol., 14: 453-466.

VAN DER KLAUW, S. N. G. C., REINECKE, T. & STÖCKHERT, B. (1997): Exhumation of ultrahigh-pressure metamorphic oceanic crust from Lago di Cignana, Piemontese zone, western Alps: the structural record in metabasites. - Lithos, 41: 79-102.

ZIMMERMANN, R., HAMMERSCHMIDT, K. & FRANZ, G. (1994): Eocene high pressure metamorphism in the Penninic units of the Tauern Window (Eastern Alps). Evidence from ^{40}Ar-^{39}Ar dating and petrological investigations. - Contrib. Mineral. Petrol., 117: 175-186.